Performance Tests of 12-Inch Multipath Ultrasonic Flow Meters

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Abstract

Accurate and cost effective measurement of natural gas flow is of major importance to the industry. Ultrasonic flow meters have the potential to significantly reduce the installation and operating costs of meter stations while providing accuracy levels consistent with, or better than, other traditional metering methods. However, a significant barrier to widespread use of ultrasonic meters in the natural gas industry is the lack of a standard covering their use. There is work in progress at both the American Gas Association and the American Petroleum Institute to assess ultrasonic meter technology and to develop a standard. The European community has also been heavily involved in research efforts to define the performance of these meters and to develop an ISO standard for ultrasonic meters. Despite the considerable numbers of tests performed to date, the need remains for more information on the performance of ultrasonic meters.

Commercially available 12-inch multipath flow meters have been tested at the Gas Research Institute's Metering Research Facility to assess baseline accuracy and repeatability over a range of flow rates and pressures, and to evaluate meter performance under disturbed flow conditions for different installation configurations. Comparisons were also made between the speed of sound as measured by the test meters and values calculated based on gas composition. These data demonstrate that the test meters are capable of accuracies well within a 1 percent tolerance and have repeatability of better than 0.25 percent when the flow rate is above about 5 percent of capacity. The data indicate that pressure may have an effect on meter error. Shifts of 0.4 percent were noted over a 650-psi range in static pressure, but errors remained within a 1 percent tolerance. The data also suggest that both the magnitude and character of errors introduced by flow disturbances are a function of meter design. Shifts of up to 0.6 percent were measured for meters installed 10 diameters downstream from a tee without a flow conditioner. Speed of sound agreement, between the measured and calculated value, was typically within 0.2 percent.

Research sponsored by Gas Research Institute under contracts 5086-271-2197 and 5095-271-3363 with Southwest Research Institute, 6220 Culebra Road, P.O. Drawer 28510, San Antonio, TX 78228-0510; telefax: 210-522-2369. Planned work cofunded by Gas Research Institute and the U.S. Department of Energy's Federal Energy Technology Center, under contact DE-FC21-96MC33033.

Additional testing of ultrasonic flow meters is continuing under funding by the U.S. Department of Energy (DOE) and the Gas Research Institute (GRI). These efforts will focus on testing of 8-inch multipath and single-path ultrasonic meters at the Metering Research Facility. A number of tests will evaluate meter performance with respect to certain gas storage characteristics, e.g., bidirectional flow, very low flow rates, and upstream thermowell effects. Field performance data will also be collected and evaluated to show the performance of ultrasonic meters under field conditions to further broaden the data available.

Acknowledgements

This work was sponsored under GRI contracts 5086-271-2197 and 5095-271-3363. The future work is being sponsored by GRI and DOE under contract DE-FC21-96MC33033. The author would like to thank Mr. John Gregor and Mr. Steve Foh at GRI and Mr. Jim Ammer at DOE for their support and guidance.

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Introduction

There are many potential benefits to the use of ultrasonic flow meters. The meters offer the possibility of cost savings in the construction or rework of meter stations where large rangeability and/or bidirectional flow is needed. The cost savings can be realized when a single meter is used to replace a bank of meters of a more traditional design (Beeson,[1] Sakariassen[2]). There may also be a substantial reduction in maintenance cost, since the meter requires no moving parts (as a turbine meter does), and the rangeability of the meter is not a function of a measurement element (as is true for an orifice plate). However, the long-term maintenance requirements have not yet been well documented. Since the meters utilize digital measurement techniques, the processor integral to the meter can provide a wealth of diagnostic information on the status of the electronic measurement system.

Because of the meter's potential, there is a great deal of interest in their application. However, the lack of an industry standard covering their use for natural gas measurement has hindered their acceptance. Other issues of concern are the lack of a substantial information base of testing information in comparison to that of orifice and turbine meters, and the difficulty in proving ultrasonic flow meters that have the capability of more flow capacity than can be tested in most calibration facilities.

Ultrasonic flow meters use measurements of the transit time of high frequency pulses between one or more pairs of transducers to determine the volumetric flowrate in the meter. The relationship between the measured transit time of an ultrasonic pulse and the average velocity along the pulse path has been well described by others (Freund and Warner,[3] Drenthen,[4] van Dellen,[5] and A.G.A.[6]).

The lengths L and X in Figure 1 can be measured on the meter spool, and the upstream and downstream transit times (t_U and t_D) are measured by the electronics. The equations indicate that measurement is inherently bidirectional based on the relative magnitudes of t_U and t_D. Equation (1) reflects that the measured path velocity is independent of the media speed of sound, and therefore is independent of the gas composition. As the meter size or velocity increases, the measured transit times and difference in transit times also increase, respectively. Both of these effects can lead to increased accuracy, but the limit occurs when the pulses no longer reach the opposing transducer. At high velocities, excessive bending of the beam path causes the pulses to miss the opposing transducer. Large diameters require sufficient signal strength for the pulses to reach the other side of the pipe. Because the transit times are determined from the detection of high frequency pulses, noise in the spectrum used by the transducer can cause errors in the measurement of the transit time. This problem can occur with low-noise pressure/flow control valves that shift audible noise to higher frequencies.

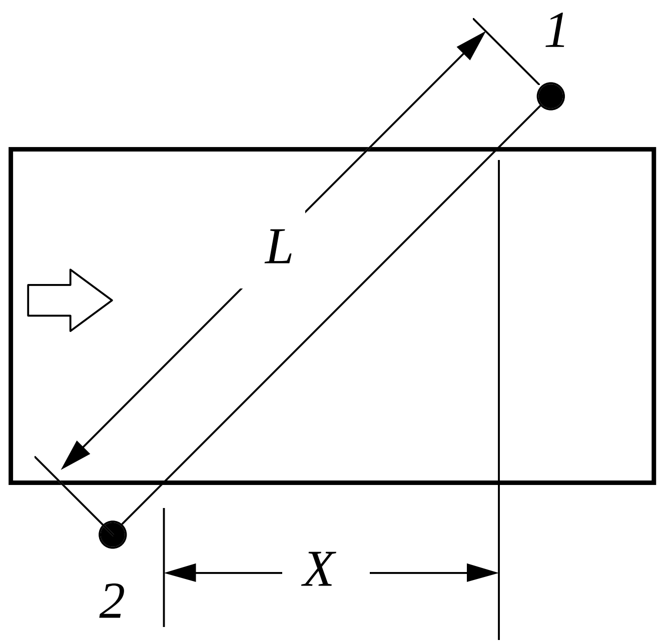

Figure 1. Ultrasonic meter geometry with transducers located at 1 and 2.

$$\text{average path velocity, } \bar{v} = \frac{L^2}{2\,X} \frac{(t_U - t_D)}{t_U\, t_D} \tag{1}$$

$$\text{measured speed of sound, } c = \frac{L}{2} \frac{(t_U + t_D)}{t_U\, t_D} \tag{2}$$

Since the meters measure the average velocity along the pulse path velocity (determined from equation (1)), a calculation is required to convert to the average axial velocity, which is used to calculate the volumetric flowrate. A weighting function can be used to combine the path velocities:

$$\text{meter average velocity, } V = \sum_{i=1}^{N} w_i\, \bar{v}_i \tag{3}$$

Although the basic relationships given in equations (1)-(3) are common to all transit time ultrasonic flow meters, there is considerable variation in path configuration, transducer type and placement, transit time measurement algorithm, and flow calculation method used by the different commercially available meters. These differences are the result of the use of different strategies to achieve the meter's target accuracy, which is typically stated as 0.5 to 1.0%. Since all of the geometric parameters needed for the flow calculation can be determined, and the non-dimensional scaling of fluid velocity profiles is understood, the meters are capable of achieving this level of accuracy without flow calibration in certain installations. Differences in meter configuration and data processing methods can affect meter accuracy, rangeability, repeatability, and susceptibility to error due to less-than-ideal installation configurations.

Objectives

As was stated earlier, a significant barrier to wide-spread use of ultrasonic meters in the natural gas industry is the lack of a standard covering their use for custody transfer applications. In response to this problem, the American Gas Association is in the process of developing a report documenting the application of ultrasonic flow meters for the measurement of gas flow. This report recognizes that, even with the significant amount of testing that has been conducted to date, there exists the need for additional information documenting the performance of ultrasonic flow meters.

The tests published to date (including those by van Bloemendaal and van der Kam,[7] van der Kam et al.,[8] Vulovic et al.,[9] and others well documented in the GERG monograph[10]) have been conducted on a variety of upstream disturbances and on different meter types and sizes, and the data indicate that under good conditions the meters perform within ±1%. These tests also show that upstream piping effects can induce errors of 0.2 to 0.8% depending on the severity of the disturbance, meter location, design, and orientation.

The purpose of these tests was to expand the information available on the performance of ultrasonic flow meters over a range of operating conditions and configurations. These test data are intended to contribute to A.G.A. and API standards development efforts.

Approach

Tests for this program were conducted in the GRI MRF High Pressure Loop (HPL) located at Southwest Research Institute. Test meters were installed in the 12-inch reference flow leg of the MRF HPL and tested with pipeline quality natural gas. Data were collected simultaneously on the ultrasonic meters and on the HPL critical flow nozzle bank, which served as the flow reference. The five binary weighted sonic nozzles were calibrated in situ at different pressures against the HPL weigh tank system (described by Park et al.[11]). The total uncertainty for the nozzles is estimated to be approximately 0.2%. An on-line gas chromatograph and equations of state from A.G.A. Report 8[12] were used to determine gas properties for all calculations. Static pressure and temperature were measured at the meters. The volumetric flowrate reported by the ultrasonic meter was acquired using different methods, depending on the meter options available from the manufacturer. For meters A1 and A2, a "calibration mode" was used, whereby the meter internally totalized the gas volume and the time during which a specific register was toggled. The average flowrate was then calculated from the totalized numbers. For meter B, reported values of actual flowrate (which were provided at a rate of one per second) were averaged to determine the average volumetric flowrate. Speed of sound measurements taken by both meters were also recorded.

A typical test sequence consisted of recirculating gas through the flow loop for a period of time to allow the gas temperature to stabilize. Steady flow was established by selecting and choking different nozzle combinations. A test point consisted of the average values of flowrate and other variables, computed over a period of 90 to 120 seconds. Test points were repeated a minimum of five to ten times to calculate an average value and standard deviation. Data were collected simultaneously from other flow measurement devices in the flow loop (typically one 10-inch orifice meter and two 12-inch turbine meters), which aided in establishing the validity and consistency of the data.

The ultrasonic meters were tested as received from the manufacturers, and all tests were conducted without the use of flow conditioners. Meters A1 and A2 were four-chordal path USMs that were "dry calibrated" by the manufacturer to measure the various lengths required for the calculations and characterize the timing delays for the ultrasonic transducer pairs. These meters had not been exposed to flowing gas prior to installation at the MRF. Meter B was a five-path USM (two double-reflecting chordal paths and three single-reflecting diametral paths) that had previously been flow calibrated and tested at several European laboratories. As received, the meter was set up for approximately 2.8 MPa operating conditions by the specification of density and viscosity values that are used for a Reynolds number calculation, which is part of the algorithm for calculation of the flowrate.

Results

Baseline

The baseline tests were conducted with the meters installed approximately 68 diameters downstream of an in-plane tee. This corresponds to meter location 3, as shown in plan-view in Figure 1. The pipe 17 diameters upstream of the meter had a surface roughness of approximately 3.8 μm and an inside diameter of 304.8 mm, which matched the diameters for meters A1 and A2 and was slightly smaller than the 306.3 mm inside diameter of meter B. The baseline testing for meters A1 and A2 was conducted with the two meters in series. The first meter was located at location 3 (Figure 1), and the second meter was located 10 diameters downstream from the first. The meters were oriented such that the chords were aligned in a horizontal plane. Baseline testing on meter B was conducted while meters A1 and A2 were installed at locations 1 and 2 (Figure 1).

Figure 2 shows the baseline performance of meters A1, A2, and B over the range of flowrates achievable in the MRF (which is 30 to 40% of full scale for a 12-inch meter). The error percentages shown are calculated relative to the nozzle bank reference flowrate.

It is apparent from the curves that all the meters are well within a 1% error tolerance, and for all but the lowest velocity, the points fall within a 0.5% band. The error bars shown on the data represent two standard deviations calculated from the data scatter at each velocity. The repeatability is similar for all the meters, having a value of less than 0.25% above approximately 1.5 m/sec. At low velocities there tends to be more scatter in the data, which is likely an effect of the resolution of the transit time measurements.

Figure 3 also shows that for meter A1, there is a small zero offset present in the meter. The offset is indicated by curvature in the meter error curve. The error changes steadily, from 0.3% when the velocity is above 1.5 to 3 m/sec, to -0.5% as the velocity approaches 0.5 m/sec. It is important to note that the zero offset present in this meter, which would normally be eliminated during the dry calibration at the factory, was knowingly left in this meter to verify its effect on the meter calibration curve. At 6.2 MPa, the estimated offset for meter A1 is 0.003 m/s.

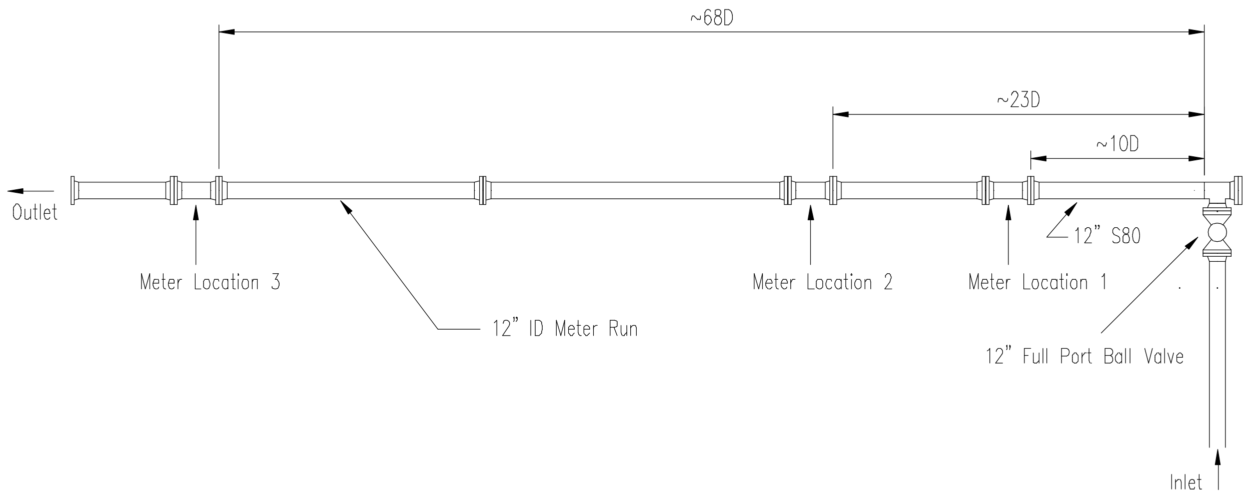

Figure 2. Meter installation for baseline and disturbed flow conditions.

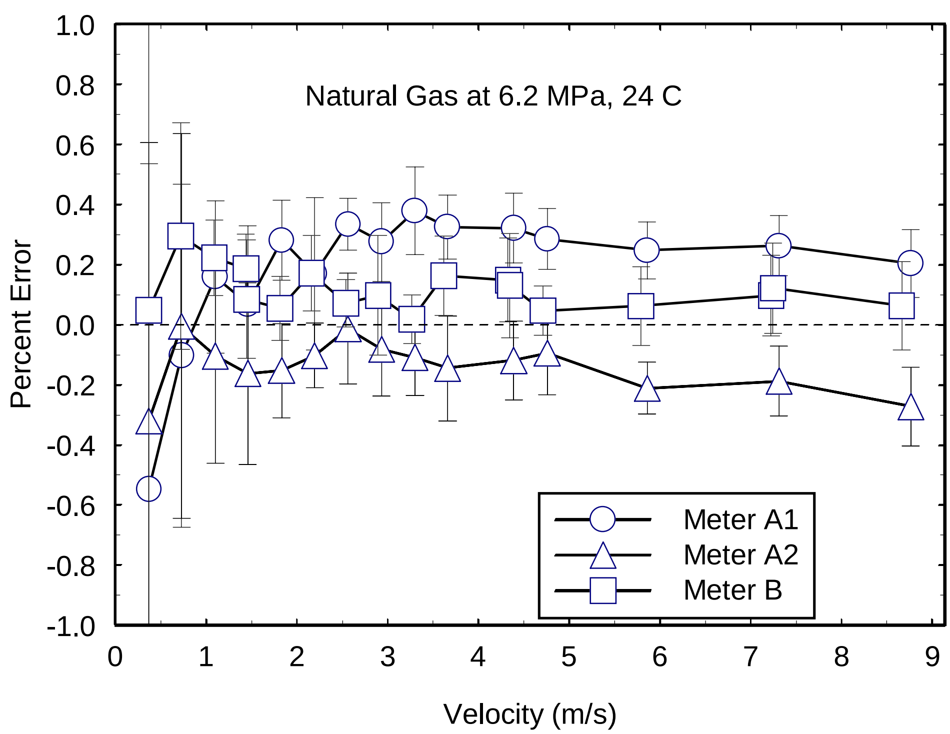

Figure 3. Baseline results at 6.2 MPa for meters A1, A2, and B.

Baseline testing was conducted at line pressures of 1.7, 2.8, and 6.2 MPa to assess any effect of pressure on the meter calibration. Figure 4 indicates the average meter error, for velocities above 2.7 m/s as a function of pressure. The data reflect a shift in the average error of about 0.4% over the 4.5 MPa range of pressures tested.

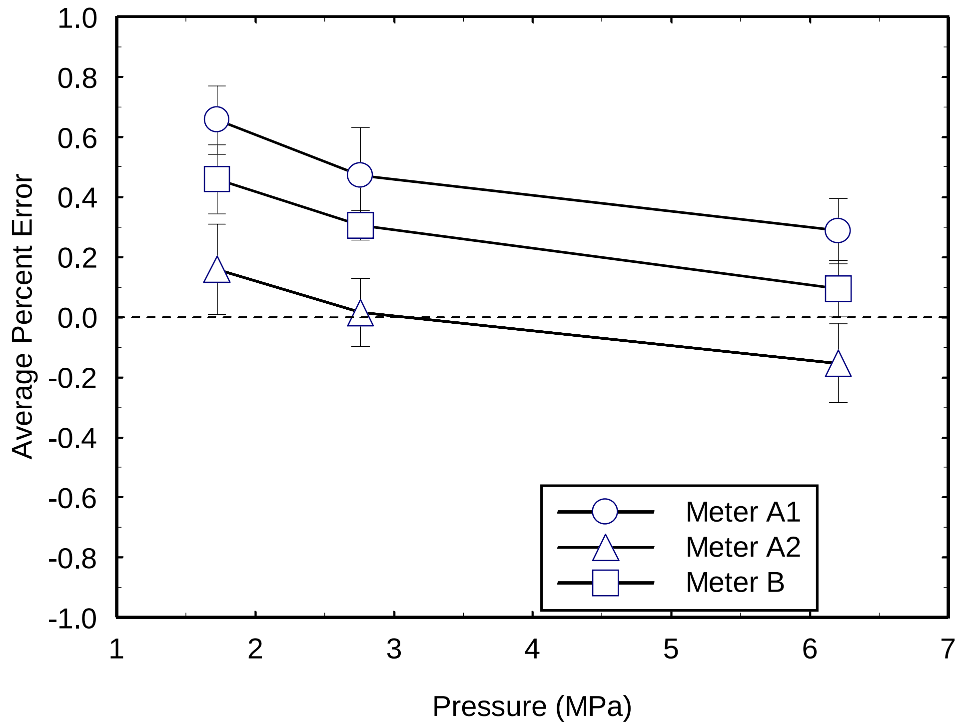

Figure 4. Average meter error as a function of pressure.

The calculation method employed by meter B uses corrections that are dependent on the velocity profile and therefore dependent on the Reynolds number. Because the density and viscosity values used by the meter were set to values appropriate for 2.8 MPa operation, a portion of the pressure shift for meter B can be attributed to the fixed values, preventing the meter from making proper corrections. A limited set of additional tests were conducted with meter B at 1.7 and 6.2 MPa, with the baseline values for the density and viscosity, and then with property values consistent with the pressure. The data indicate shifts of roughly 0.1 percent towards the 2.8 MPa line for the 1.7 MPa case and essentially no change for the 6.2 MPa case.

The change in the path length and meter body diameter as the pressure is increased also introduces an error into the measurement. However, the estimated change in calibration, due to mechanical deformation, is less than 0.05% for the 4.5 MPa change in pressure. These results are contrary to the findings of other testing (van Bloemendaal and van der Kam,[7] Vulovic et al.[9]) where no consistent dependence on pressure was identified (although there were variations in the mean error at different pressure levels). Because the data available in the aforementioned studies came from multiple laboratories and were presented in summary fashion, it is difficult to distinguish differences that are related only to pressure versus differences that are a result of small biases between laboratories. The results from the five test facilities show variations of about ±0.6% over a 10:1 turndown in the meter operating range for pressures between 1 and 6 MPa. The effect of pressure needs to be investigated further to fully explain the data. Additional work to accurately model the measurement process used by ultrasonic meters may offer possible explanations.

Speed of Sound

Figure 5 shows the percent error between the speed of sound reported by the meters and that derived from A.G.A. Report 8[12] density calculations based on the measured pressure, temperature, and gas composition. The figure shows that the error is typically less than 0.2% for both test meter types, with each meter type having its own bias relative to the calculated value. The figure confirms that the reported speed of sound is not dependent on the gas velocity. The meter velocity was used as the independent axis in the figure because of the limited range of speed of sound information available from the data shown in Figure 5 (sound velocities ranged from 414 to 430 m/sec). The data for meter A1 show more scatter than the meter B data. Although not presented in Figure 5, the data for meter A2 were similar to those for meter A1. There does not appear to be a large dependence on pressure, with about 0.1% shift between the 6.2 MPa data and the results for the other pressures.

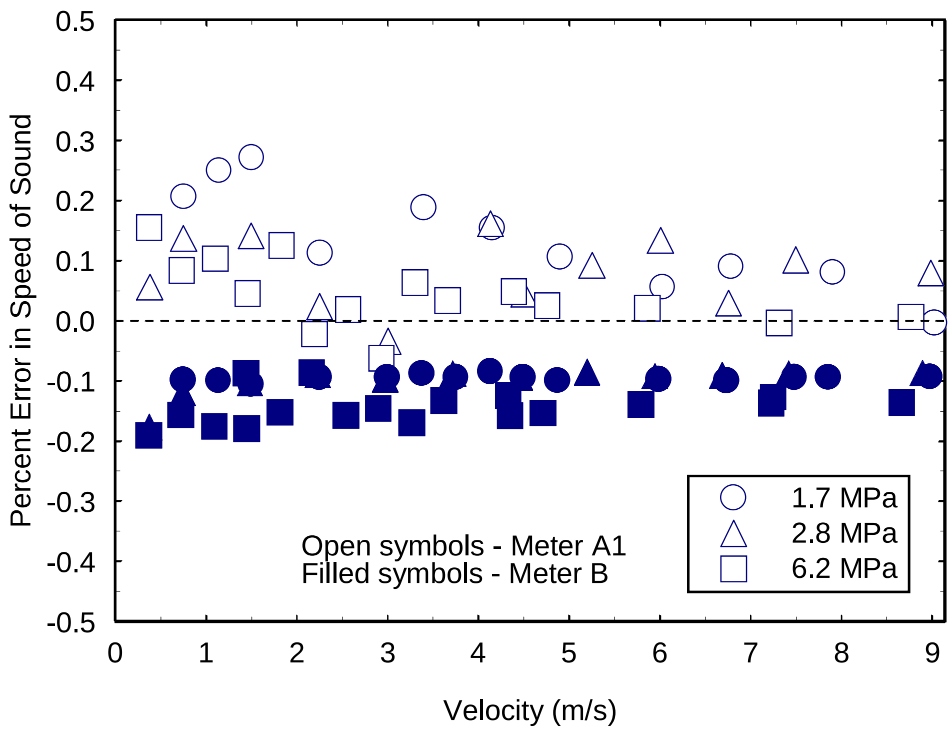

Figure 5. Comparison of speed of sound for meters A1 and B.

These results indicate that the level of agreement to be expected under controlled conditions is on the order of the uncertainty in the speed of sound calculated from the gas composition. It should be recognized, however, that because of the relationship between the path velocity and path speed of sound measured by the meter, good agreement between the calculated speed of sound and that reported by the meter is not a sufficient condition for accurate flow measurement.

Disturbance Tests

Figure 2 showed that the location of the meters for the disturbance tests was 10 diameters downstream of a tee (i.e., meter location 1 on Figure 2) located just downstream from a 12-inch diameter full-port ball valve. Tests were conducted with the ball valve open, and at two partially closed positions (to increase the level of flow disturbance entering the test meter). No flow conditioner was installed upstream of the meter. The piping between the tee and the meter was 12-inch schedule 80 pipe having a nominal inside diameter of 288.9 mm (and surface roughness of approximately 8.9 μm). Therefore, when located at the position 10 diameters down from the tee, the meter was subjected to a combination of the effects of the 15.9 mm concentric step in diameter (an 11% increase in area), the tee, and for some tests, a partially closed valve. Tests were conducted at the same three pressures used for the baseline calibrations. A set of scoping tests were also performed with the meter located 23 diameters downstream from the tee (meter location 2 on Figure 2.)

Meter A1 was tested in two different orientations relative to the tee. The 0 degree position had the chords aligned in a horizontal plane along with the tee. The meter was also rotated 90 degrees, so that the chords were aligned in a vertical plane. Meter B was tested in only one orientation.

Figure 6 displays the results for the upstream disturbance testing at 2.8 MPa. Although the data appear to differ from the initial baseline, additional baseline data collected just prior to the initiation of the disturbance tests revealed a shift. (It was later discovered that this shift may have been due to a failing chord.) The data at 23D can be considered as the revised baseline. Relative to the 23D (revised baseline) results, the data for 10D with the chords horizontal (0°) are shifted by about 0.1% to 0.2%. The results for the dependence on the meter orientation indicated a shift of about -0.4% when the chords are vertical (90°). The fact that there are differences dependent on the chord orientation relative to the disturbance is not surprising, and these differences have been measured by others (van Bloemendaal and van der Kam[7]). Since the transit time measured by the meter for a particular path is dependent on the average velocity along the path, the paths cutting across the disturbance tend to average out the effect of the disturbance. When the paths are vertical and the primary direction of velocity disturbance is horizontal, the ability of the integration method to accurately resolve the average velocity has more of an effect on the results.

Also shown in Figure 6 is the effect of the partially closed valve on meter performance. The results indicate that the valve position had little effect on the average error of the repeated runs, but there was a small increase in the data scatter, suggesting that turbulence levels were increased as a result of closing the valve.

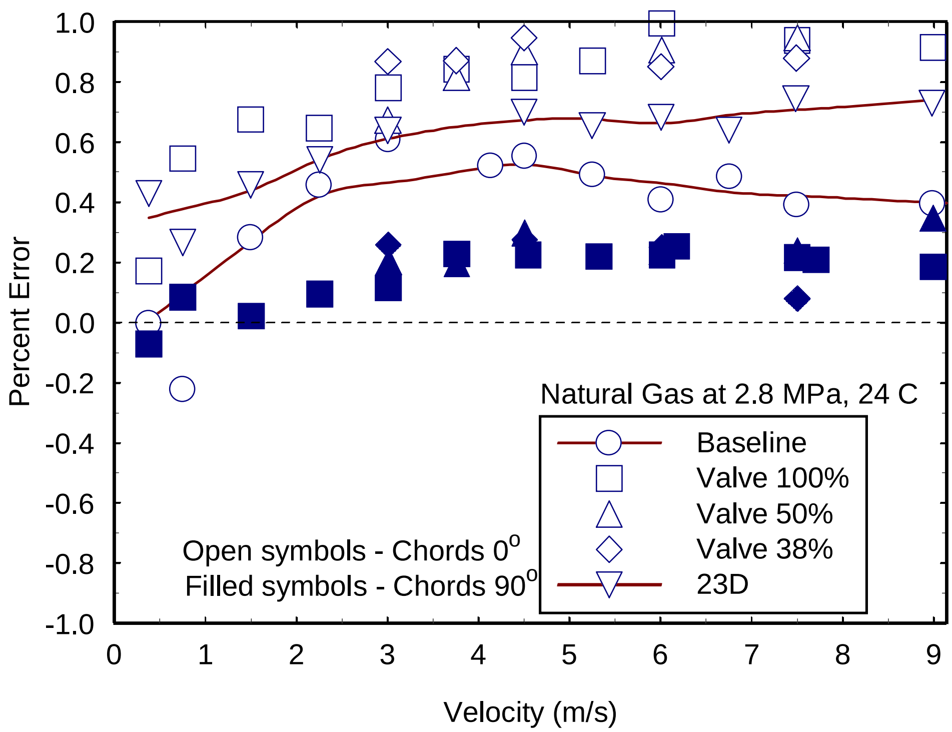

Figure 6. Performance of meter A1 10D downstream of a tee at 2.8 MPa.

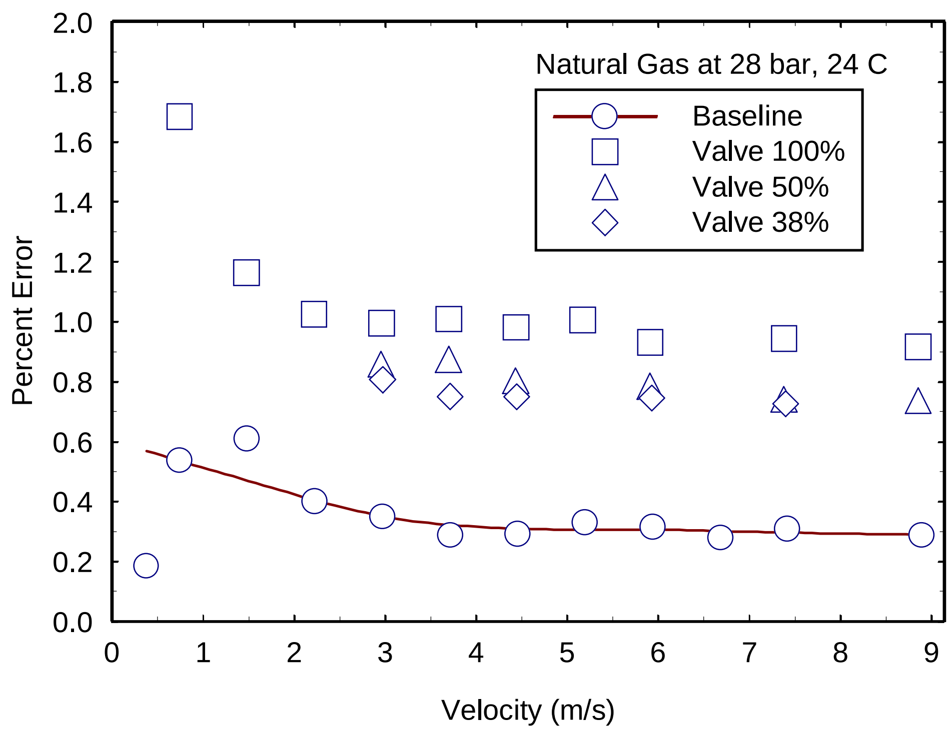

Figure 7. Performance of meter B 10D downstream of a tee at 2.8 Mpa.

Figure 7 gives the results for meter B installed 10D down from the tee. The results show a shift of about 0.6% from the baseline with the valve fully open and a shift of about 0.4% from the baseline when the valve is partially closed (50% and 38% open). The result was unanticipated, since the partial blockage by the valve was expected to increase the flow distortion. The valve position influenced the absolute value of the error, but did not have a significant effect on the data scatter of the repeated runs. Data reported by Vulovic et al.[9] showed a deviation of 0.3% relative to the baseline when the meter was installed 10D down from an elbow. The effect of the 15.9 mm step change in pipe diameter in the MRF installation may account for the difference in results as compared to those of Vulovic et al.,[9] where no step was indicated in the description of the test.

The results of the disturbance testing conducted at 1.7 and 6.2 MPa indicate results similar to those shown here for 2.8 MPa for both meter types, and they have been reported elsewhere (Grimley[13]).

Application

These results can be applied to meter station design to realize the level of accuracy that can be achieved using ultrasonic meters. The results also indicate the potential measurement bias that may exist in a meter that has not been flow calibrated. The station designer should recognise that the meters are not completely insensitive to the upstream piping configuration and that different meters respond differently to flow disturbances. Since these tests were limited to a single type of disturbance, the results are not sufficient to provide detailed guidelines for installation requirements.

Future Activities

Ongoing activities sponsored by DOE and GRI include tests that focus on 8-inch ultrasonic flow meters. Test objectives include:

- Establishing baseline performance of the meters to be tested over a range of operating conditions.
- Establishing the effect on performance of reversing the flow direction relative to the meter.
- Assessing the effect of disturbances caused by the presence of a thermowell immediately upstream of the meter.
- Assessing the effect on the meter of disturbed flow created by the presence of one or more elbows in typical piping configurations.
- Assessing the use of flow conditioners to reduce flow measurement shift caused by typical piping configurations.

The tests will be conducted with commercially available 8-inch diameter single-path and multipath ultrasonic flow meters using the methods described previously in this paper. The program currently includes two Instromet meters: a single-path P.Sonic and a 3-path Q.Sonic; and two Daniel meters: a 4-path SeniorSonic and a dual path meter (which will be treated as two single-path meters). Meters were solicited from other manufacturers, but the meters were still under development. The possibility still exists to include additional manufacturers' meters later in the program.

The intent is to test each meter in each of the configurations described in this plan. A set of scoping tests will be performed using an installation that meets the A.G.A. Report Number 7[14] minimum installation guidelines (which are specific to turbine meters).

In addition to the testing with the 8-inch meters, gas industry members with ultrasonic meters installed in the field are being solicited to make their data available to further expand the available information. The field data will be collected and analyzed by SwRI under co-funding from GRI and DOE.

Acknowledgments

This work was sponsored under GRI contracts 5086-271-2197 and 5095-271-3363. The future work is being sponsored by GRI and DOE under contract DE-FC21-96MC33033. The author would like to thank Mr. John Gregor and Mr. Steve Foh at GRI and Mr. Jim Ammer at DOE for their support and guidance.

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